

The Cosmic MeV Neutrino Background as a Laboratory for Black Hole Formation

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Calculations of the cosmic rate of core collapses, and the associated neutrino flux, commonly assume that a fixed fraction of massive stars collapse to black holes. We argue that recent results suggest that this fraction instead increases with redshift. With relatively more stars vanishing as “unnoae” in the distant universe, the detectability of the cosmic MeV neutrino background is improved due to their hotter neutrino spectrum, and expectations for supernova surveys are reduced. We conclude that neutrino detectors, after the flux from normal SNe is isolated via either improved modeling or the next Galactic SN, can probe the conditions and history of black hole formation.

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Introduction.— The dearth of supernovae in our own galaxy leads us to examine those that occur throughout the universe in order to study the physics underlying the collapse of massive stars, which is vital for understanding stellar life and death [1–8]. Observations of the classes of SNe attributed to core collapse – Types II, Ib, and Ic – have advanced greatly in the past decade, and the most recent measurements of their rates now cover out to a redshift of $z \gtrsim 1$ [9–16].

In Fig. 1, we see that these data are close to, yet do not quite match [17], the assumption that all $\gtrsim 8 M_\odot$ stars explode as supernovae [18]. However, some subset of core collapses must result in the massive black holes seen in the Milky Way and beyond. Despite many years of research [19–24], the fraction that do so remains uncomfortably uncertain. One option is to search for stars in nearby galaxies that simply disappear, i.e., unnoae [25] (throughout, we refer to collapses that yield a bright optical transient as “SNe” [26] and others as “unnoae”).

Fortunately, even if no photons result from their core collapse, stars do not vanish entirely without a trace. Such massive progenitors yield, if only for an abbreviated period, protoneutron stars that emit copious amounts of neutrinos, with a hotter spectrum than in a lower-mass collapse [27–33]. Thus, in addition to the diffuse supernova neutrino background (DSNB) from successful explosions ([34–41]; see [42, 43] for a comprehensive review), unnoae should contribute to the overall cosmic MeV neutrino background (CMNB) (e.g., [44–46]).

While studies of the CMNB have assumed that a constant fraction of core collapses result in unnoae rather than supernovae, we argue that recent studies imply that this fraction is larger in the more distant universe than locally. This is because lower stellar metallicity points toward a greater propensity for black hole formation [22, 23] and metallicities were lower at higher redshift. Since present theoretical uncertainty prevents first principles modeling of the cosmic unnova rate, we draw guidance from gamma-ray bursts (GRBs), which in the collapsar model arise from core collapses yielding rapidly-

rotating black holes ([47]; cf. [48]). GRB observations have also greatly improved, revealing a sensitivity to metallicity (e.g., [49, 50]) in accord with theory [51, 52].

We use observations of cosmic gamma-ray bursts, which display a stronger evolution with redshift than the star formation rate (SFR) alone [53–58], as an empirical proxy for the total unnova rate to capture the variation due to metallicity. This approach is qualitatively different from past studies, containing an expectation that the rate of cosmic SNe should not simply scale from the SFR,

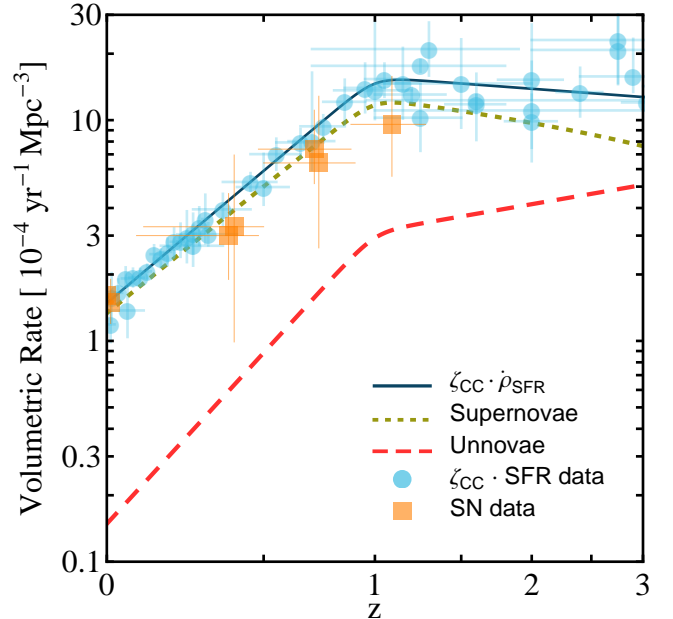


FIG. 1: The cosmic rate of core collapse. Shown are recent measurements of core-collapse supernovae [9–12] (*squares*; see [17] for older data), which fall just below the expectation from star formation rate data with all stars of mass $\gtrsim 8 M_\odot$ yielding optical SNe (*circles*; [18]). These are compared to our model assuming a local 10% rate of unnoae that evolves with z (*dashed*), the predicted SN rate (*dotted*), and the total (*solid*).

instead displaying an offset that grows with increasing z . This may already be hinted at by the data in Fig. 1.

This evolution is crucial for the CMNB, since the unnova fraction at $z \sim 1$ would be larger than in the metal-enriched nearby universe. Combining recent core-collapse neutrino flux simulations from [33] with modern measurements of the cosmic star formation rate and an evolving rate of black hole formation, we find that unnovae can be the dominant component of the CMNB, even if disappearing star surveys do not find anything locally.

As experimental limits near the expected level of the CMNB [59–62], such an approach as we present is needed for a proper interpretation of the eventual discovery. We examine the capabilities of future large water detectors (e.g., [63–65]) to extract the properties of neutrino emission from black hole formation. We further discuss complementary observations that can be made, such as of Type Ibc SNe, along with a variety of implications.

Neutrino spectra from core collapse.— For water Cherenkov detectors, the principal detection channel of the CMNB is inverse beta decay, $\bar{\nu}_e + p \rightarrow n + e^+$, so our primary interest is in the total $\bar{\nu}_e$ flux arriving at Earth from distant core collapses. We consider two scenarios for the SN contribution. The first takes the time-integrated spectrum from SN 1987A data [66, 67], as inferred in [40], as representative of all SNe. This spectrum, shown in Fig. 2, has $\langle E_{\bar{\nu}_e} \rangle = 12$ MeV and $\mathcal{L}_{\bar{\nu}_e} = 6 \times 10^{52}$ erg. This has the advantage of naturally including any oscillation effects on the outgoing spectrum, but suffers from sampling only one star with limited statistics. For comparison, we also display a Fermi-Dirac spectrum with $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV and $\mathcal{L}_{\bar{\nu}_e} = 5 \times 10^{52}$ erg, as is often used.

As an alternative, we consider the results of Nakazato et al. [33], who combined general relativistic radiation hydrodynamical simulations, assuming shock revival at either 100, 200, or 300 msec after bounce, and protoneutron star cooling until 20 sec to find neutrino light curves and spectra for four progenitor masses (13, 20, 30, and $50 M_\odot$) at two metallicities ($Z = 0.02$ or 0.004). We show the time-integrated $\bar{\nu}_e$ spectrum for $13 M_\odot$ and $Z = 0.02$ in Fig. 2, using the 100 msec model to be conservative. Convoluting the models over a Salpeter mass function yields a very similar spectrum. Since other flavors have similar spectra, modifications due to neutrino mixing or neutrino-neutrino interactions (e.g. [68–71]) should be small, so we use this spectrum in determining the DSNB.

Nakazato et al. found that their $30 M_\odot$, $Z = 0.004$ model yielded a black hole. The time-integrated $\bar{\nu}_e$ spectrum [33] is shown in Fig. 2 and is seen to be far harder than from SNe. We will use this as the template for the unnova contribution to the CMNB. In general, the flux from black hole production will depend on the progenitor and the nuclear equation of state [29–32].

Cosmic core-collapse rates.— The cosmic star formation rate history $\dot{\rho}_*(z)$ has become much clearer in recent years. If every star that forms with a mass $> 8 M_\odot$ ends with a core collapse, assuming a Salpeter mass func-

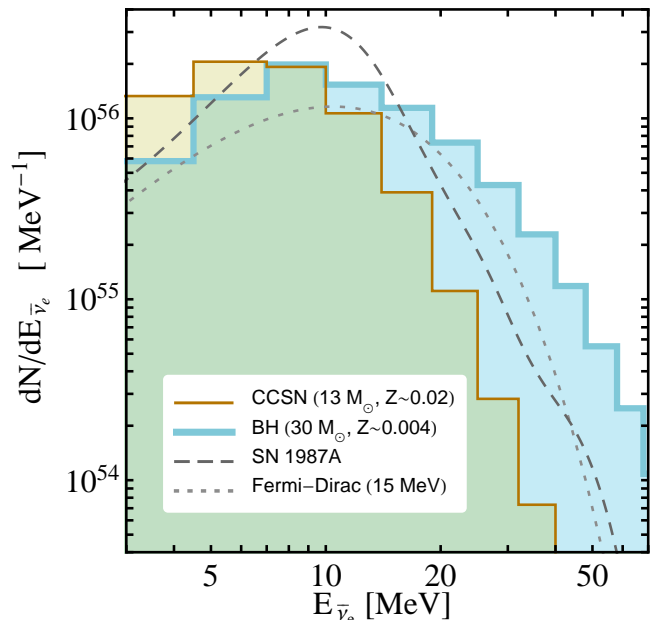


FIG. 2: The $\bar{\nu}_e$ spectra used in this study. Shown are those from the $13 M_\odot$ ($Z = 0.02$, 100 msec revival) SN simulation of Nakazato et al. (*thin solid*), their $30 M_\odot$ model yielding a black hole (*thick solid*) [33], and the SN 1987A model of [40] (*dashed*). These are compared to a Fermi-Dirac spectrum with $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV and $\mathcal{L}_{\bar{\nu}_e} = 5 \times 10^{52}$ erg (*dotted*).

tion that continues to $100 M_\odot$ yields $\dot{n}_{CC}(z) = \zeta_{CC} \dot{\rho}_*(z)$, with $\zeta_{CC} = 0.0074/M_\odot$, as shown in Fig. 1 for both the SFR data compiled in [18] and the parametrized form from [72, 73]. (The IMF dependence is small, see [18].)

Measurements of the cosmic rate of core-collapse supernovae have also greatly improved. In [17], it was noted that such SN data was lower by a factor of ~ 2 than the inferred $\dot{n}_{CC}(z)$. In Fig. 1, we see that the latest measurements [9, 11, 12] narrow this to a degree, although a gap persists at increasing z . The fraction of core collapses that fail to produce a SN, and thus cannot be counted by SN surveys, remains largely unconstrained. However, the presence of stellar-mass black holes, e.g., seen in binaries [74], requires a non-zero birth rate.

Theoretical studies suggest that the black hole rate should increase with decreasing metallicity, largely due to decreased mass loss [5, 22, 23]. The rate of Type Ib/Ic SNe, which are believed to arise from very massive stars that have lost their envelopes due to metal-line driven winds [5], may then be suppressed if such stars fail to explode. The extensive survey conducted by the Lick Observatory Supernova Search (LOSS) found that the SN Ibc to core collapse ratio decreases by a factor of ~ 3 in galaxies at $\lesssim 10^{10} M_\odot$ (see Fig. 23 in [13]). Indeed, observations at low redshift show a substantial drop in the average metallicity of galaxies below $\sim 10^{10} M_\odot$ [75].

Since the universe was less metal-enriched at higher redshifts, we pursue an evolving model for the cosmic un-

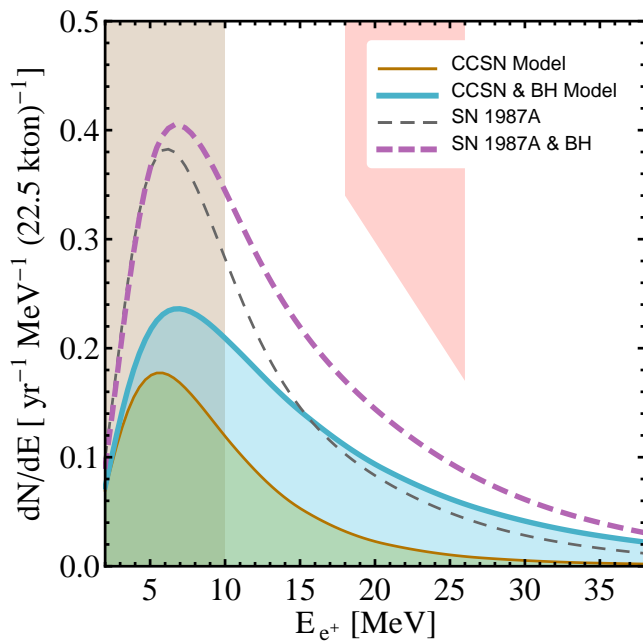


FIG. 3: The positron production spectrum in 22.5 kton Super-Kamiokande for our cosmic MeV neutrino background models (as labelled). Denoted are the regions where reactor antineutrinos dominate (below 10 MeV) and the inferred limits (from 18–26 MeV) based on 2003 Super-K data [59] from [41] (2012 Super-K limits are model dependent [62]).

nova fraction. We follow the indications given by bright gamma-ray bursts from [57] of a rate that evolves more strongly than the SFR by a factor of $\sim (1+z)$. Fig. 1 shows an unnova fraction that is 10% of the total core-collapse rate locally and grows with z (*dashed line*).

Fig. 1 also displays our expected SN rate (*dotted line*). It is possible that the threshold mass for core collapse itself depends on metallicity, although a decrease below $8 M_{\odot}$ would likely increase the rate of low-luminosity O-Ne-Mg explosions [76–80]. Such events may add to the total rate of SN occurrence, but not necessarily increase the observed rate of SNe. Since corrections of high-redshift data due to incompleteness of such faint events are based on local observations, where the metallicity is highest, we do not attempt an additional correction.

TABLE I: CMNB event rates in various ranges of visible energy from the spectra displayed in Fig. 3. All quoted values are per 22.5 kton yr (per 0.560 Mton $\times 10$ yr).

Range (MeV)	4-10	10-18	18-26
CCSN Model	0.95 (238)	0.54 (135)	0.14 (36)
CCSN & BH Model	1.34 (335)	1.25 (314)	0.65 (162)
SN 1987A	2.09 (523)	1.40 (350)	0.56 (139)
SN 1987A & BH	2.26 (566)	1.97 (492)	1.00 (249)

The Cosmic MeV Neutrino Background.— The flux of neutrinos from cosmic core collapses depends on their spectra and rate history, as discussed above, as well as the cosmology assumed. Including the cross section for inverse-beta decay $\sigma(E_{\bar{\nu}_e})$ [81, 82], we obtain the positron spectrum in the detector in terms of $E_{e^+} = E_{\bar{\nu}_e} - \Delta$, where $\Delta = M_n - M_p$, as

$$\psi(E_{e^+}) = c \sigma(E_{\bar{\nu}_e}) N_t \int_0^{z_{\max}} \frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}} \frac{dE'_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} \frac{\dot{n}(z)}{dz/dt} dz,$$

where $dz/dt = H_0 (1+z) [\Omega_m (1+z)^3 + \Omega_{\Lambda}]^{1/2}$ (with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km/s/Mpc) and $dE'_{\bar{\nu}_e}/dE_{\bar{\nu}_e} = (1+z)$ accounts for redshift. For a 22.5 kton fiducial volume, such as Super-Kamiokande, $N_t = 1.5 \times 10^{33}$.

In Fig. 3, we present the positron spectra obtained from our models discussed above for $dN_{\bar{\nu}_e}/dE_{\bar{\nu}_e}$ and $\dot{n}(z)$, in which the contribution is either entirely from SNe (*thin solid and dashed lines*; i.e., the typical DSNB) or from a combination of SNe and unnovae as in Fig. 1 (*thick solid and dashed lines*). In Table I, we provide event rates from these models in given energy ranges.

We see that unnovae could contribute more than half of the CMNB in the 10–20 MeV range and easily be the dominant contribution above 20 MeV. If backgrounds are reduced by the addition of gadolinium [83], these should be detectable. The improved capabilities of Super-Kamiokande IV were recently shown to allow detection of the 2.2 MeV gamma-ray associated with $n + p \rightarrow d + \gamma$ with a $\sim 20\%$ efficiency [84, 85], already permitting at least partial tagging of inverse-beta events.

In Fig. 4, we follow the procedure of [39] to determine what would be inferred from the detailed observations of the CMNB afforded by a 560 kton detector such as Hyper-Kamiokande (with Gd). This imposes a Fermi-Dirac spectrum with cosmic evolution following the star formation rate from Fig. 1. We reconstruct both 2σ (*lines*) and 5σ (*shaded*) allowed regions in the temperature versus luminosity plane if the observed signal follows one of the four scenarios in Fig. 3, using only the 10–20 MeV range in which background should be lowest [83].

We see that, if unnovae are as important as suggested and are not accounted for properly, the inferred SN $\bar{\nu}_e$ temperature and luminosity would be ~ 5 MeV and $\mathcal{L}_{\bar{\nu}_e} \sim 3\text{--}5 \times 10^{52}$ erg, which are far from the “true” values for normal SNe used. For example, if the SN 1987A model (*thin dashed line*) represents the true SN spectrum and the measured CMNB suggests a harder and more energetic spectrum (*thick dashed line*), a significant unnova contribution could be established at $> 5\sigma$.

Even lower unnova contributions ($\lesssim 3\%$ of the local CC rate with $1+z$ evolution) can be probed provided we have a reliable a priori spectrum for SNe. If we cannot make such an assumption, it is more challenging to establish the precise contributions solely based on CMNB observations. This is illustrated in Fig. 4 by the overlap in the allowed regions for the SN 1987A (*thin dashed*) and CCSN & BH (*thick solid*) models, which shows that a

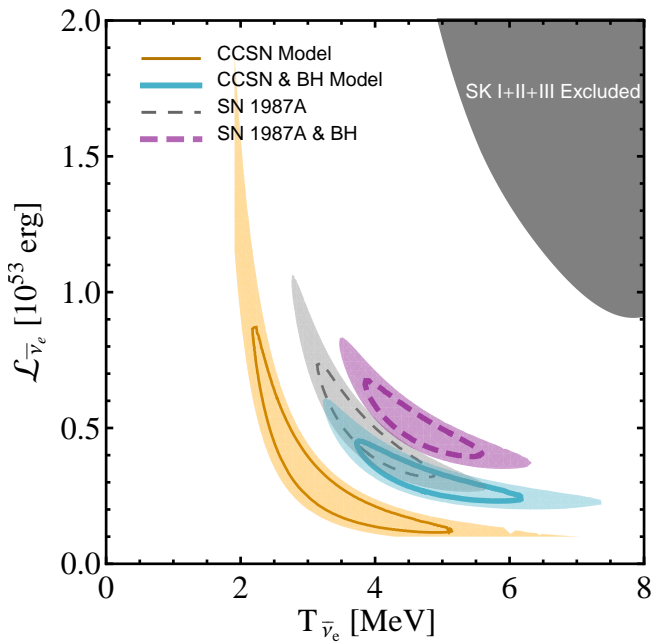


FIG. 4: Inferred constraints on the combination of SN $\bar{\nu}_e$ temperature and luminosity expected in a 560 kton detector (i.e., Hyper-Kamiokande) in 10 years if a Fermi-Dirac spectrum was naively assumed. Shown are the four models from Fig. 3; lines (shades) correspond to 2σ (5σ) contours. We see that, if unnovae were not accounted for, the reconstructed properties of “SNe” (as exhibited by thick contour sets) would be far from the “true” values (thin contour sets).

relatively-cold supernova and relatively-hot unnova combination could mimic a signal based on SN 1987A alone. However, observing a Galactic SN will greatly improve upon the SN 1987A data. Note that even if uncertainty in the overall core-collapse rate causes an overall shift along the \mathcal{L} axis, temperature information still allows for separation of the relative contributions. This is important since it is unlikely that we will ever measure the neutrino output of a Galactic unnova, leaving the conditions of black hole formation, and their fraction in the high-redshift universe, purely in the realm of CMNB studies.

Discussion and Conclusions.— A common question is: What can actually be learned from detecting the cosmic MeV neutrino background? We have attempted to show an important application. That core-collapse events occur that produce black holes is inevitable, although the rate remains highly uncertain. Our first and foremost conclusion is that a significant portion of the CMNB could be due to black holes even if the local rate is low (a 10% local unnova fraction is near the limits of a 10 year “survey about nothing” for disappearing massive stars [25]), with gamma-ray bursts providing a guide on how to proceed. This is due to the metallicity evolution of the universe yielding relatively more such events at higher redshifts, which would also affect expectations for nucleosynthesis, as well as feedback, in young galaxies.

We have seen that the CMNB is likely detectable in

Super-K, even if the neutrino spectrum from SNe is colder than often assumed, as with the simulations of [33] that form the DSNB in one of our models, as long as there is appreciable black hole production. Other than the possibility of detecting minibursts of neutrino events from core collapses in nearby galaxies with Mton-scale detectors [86–89], the CMNB provides the only imminent means of testing simulations of the processes occurring deep within the dying star.

It is evident that in this case it will be difficult to determine the average neutrino spectrum from the SNe that form the DSNB, which is subdominant. However, a new window opens on the study of the formation of black holes. This is particularly important since the Milky Way is an evolved, metal-enriched galaxy, with an unnova rate that is likely lower than in the distant universe, making this even more difficult to probe directly.

The parametrization of evolution that we use likely saturates at some redshift. It would thus be useful to estimate the unnova rate directly. To do so via the difference between SFR and SN data requires consideration of binary interactions amongst massive stars. In [90], it was suggested that $\sim 25\%$ of massive stars will be involved in a merger. As interactions depend on the binary mass ratio and orbital period, any massive stars lost to mergers with a more massive star prior to core collapse would likely be from lower masses. The SN rate may then be reduced by a factor f_m , perhaps $\sim 5\%$. Mergers could lead to more unnovae, since more high mass stars might be made than merged away, although the net effect of binary interaction is unclear. This has not been included previously and we defer a more detailed account.

When a Galactic SN does occur, this could be used as a detailed template for subtraction of the DSNB, utilizing the measured rate of visible SNe, to arrive at the naked black hole contribution. Improved knowledge of the nuclear equation of state, which affects the black hole transition and associated neutrino output [29, 32], may well be independently obtained [91], further enhancing the extraction of physics from the CMNB.

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